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Underground Exploratory Studies

The Yucca Mountain Exploratory Studies Facility

Dr. Mark T. Peters
Argonne National Laboratory
United States Department of Energy

Overview

- Exploratory Studies Facility and Cross Drift
 - Testing and Data Collection
 - Geology and Rock Properties
 - Hydrology
 - Geochemistry
 - Coupled Processes
- Busted Butte Transport Test Facility
- Summary

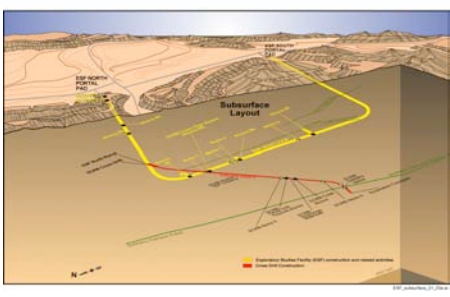
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Exploratory Study Facilities and Alcoves



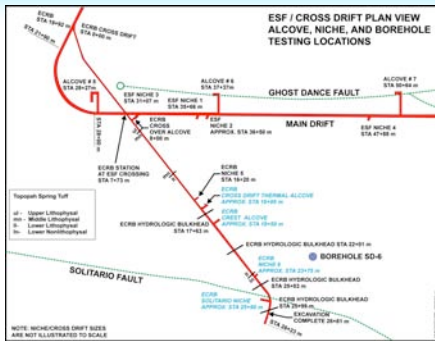
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Exploratory Study Facilities and Alcoves



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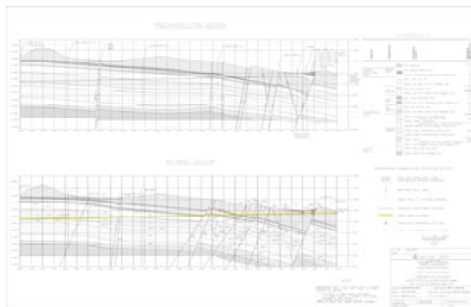
Geology and Rock Properties

- Geologic mapping (including pre-excavation predictions)
- Consolidated sampling
- Laboratory studies
 - Thermal rock properties
 - Thermal-mechanical rock properties
- Field studies
 - Thermal rock properties
 - Thermal-mechanical rock properties
 - Construction monitoring
 - Seismic monitoring

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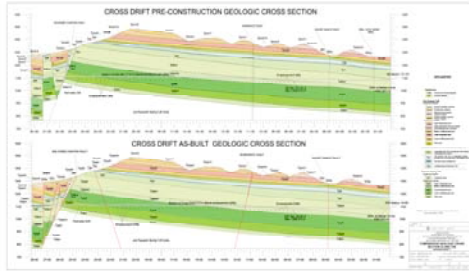
ESF North Ramp Geology



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Cross Drift Geology



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Lithophysal / Fracture Studies

- Objective is enhanced understanding of fracture geometry and relations to lithophysae -- important link to thermal and mechanical properties investigations
- Methods of Lithophysal Data Collection
 - Visual estimates – entire Cross Drift (1998)
 - Panel Maps – 1 X 3 m photomosaics - Topopah Spring Lower Lithophysal (Tptpl)
 - Tape Traverses – Physically measured “line” traverses on 5m centers throughout the Tptpl
 - Angular Traverses – Laser traverses at selected locations in the Tptpl
 - Large Lithophysae Survey – Locating only lithophysae >50 cm in size in upper Tptpl

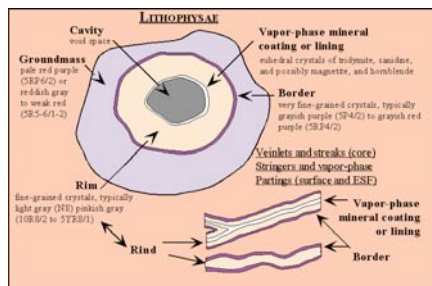
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Lithophysal / Fracture Studies (Continued)

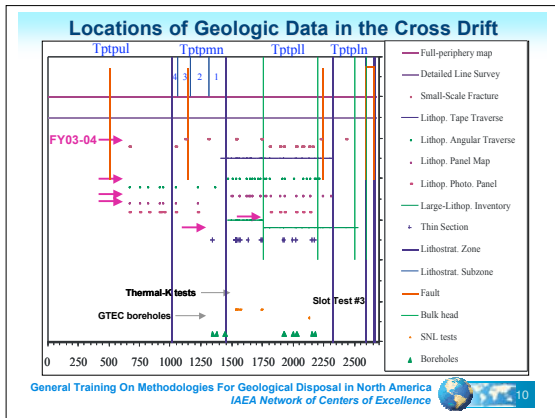
Lithophysae, Spots, and Vapor Pathways

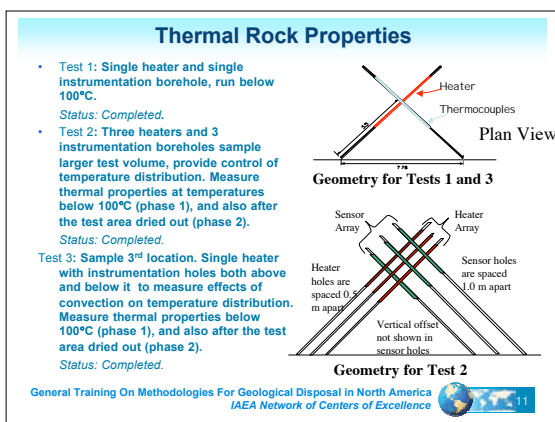
(spots are the same as lithophysae, but do not have cavities and vapor-phase mineral coatings)

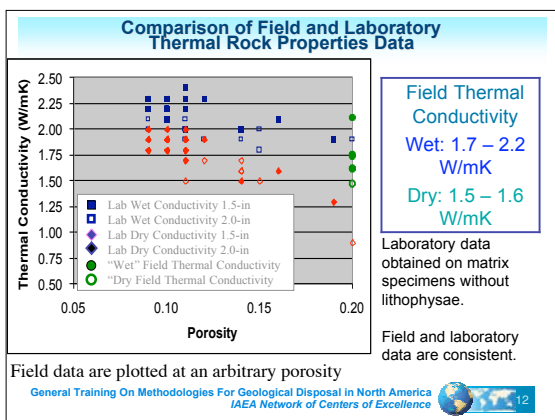


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Thermal-Mechanical Rock Properties

- Objectives
 - Provide data in support of ground support design, rockfall models, and thermal models
- Status
 - In situ field tests complete
 - Laboratory measurements ongoing



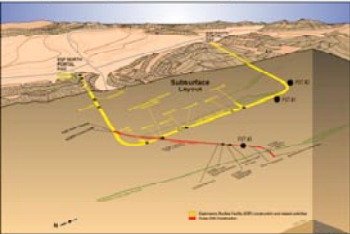

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Thermal-Mechanical Rock Properties (Continued)


Pressurized Slot Test Locations

Exploratory Studies Facility and Alcoves






PST #1 – Station 57+77 of ESF, Tptpl (Completed)
PST #2 – Station 63+83 of ESF, Tptpl (Completed)
PST #3 – Station 21+25 of Cross Drift, Tptpl (Completed)

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Thermal-Mechanical Rock Properties (cont.)

Uniaxial Compression Tests of the 11.5" diameter upper lithophysae samples (7-8/02)

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Hydrology

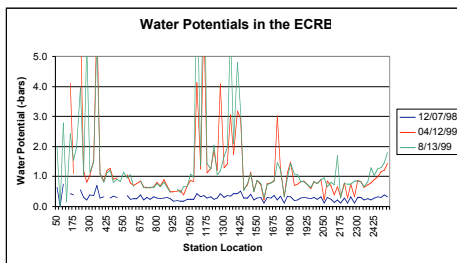
- Consolidated sampling
- Laboratory studies
 - Hydrologic properties
- Field studies
 - Moisture monitoring
 - Alcove and niche testing - flow and transport processes
 - Robust approach to testing and modeling
 - Scoping analyses in support of test design
 - Pre-test predictive modeling
 - Predictions compared to measurements lead to model refinement and validation
 - Some data also supports model calibration

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Moisture Monitoring

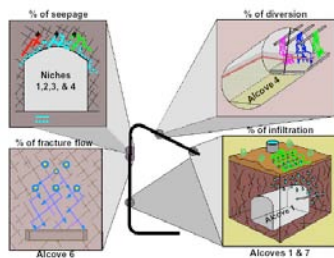


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In Situ Testing in ESF




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ALCOVE 1

Infiltration & Percolation Study – El Niño Study




PURPOSE:

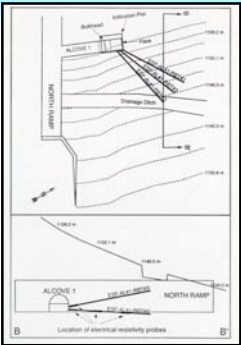
- Monitor the climatic effects associated with an increased rainfall event
- Evaluate the process of surface water infiltration and subsequent percolation through the unsaturated zone above Upper Tiva Canyon Alcove




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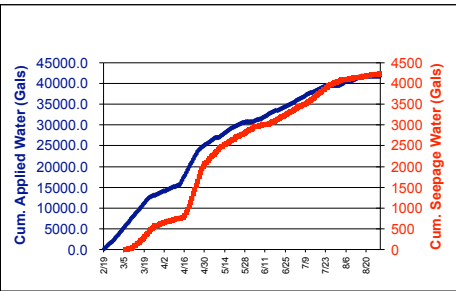
Alcove 1 Layout




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Alcove 1 Infiltration Experiment



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The Testbed

Access 6

Typical Tunnel

Up
North
East

Niche 3

[illegible]

- Spatial/temporal variability in infiltration and seepage rates
- Development of distinct flow paths
- Tracer test ongoing



A 3D schematic diagram of a cable joint assembly. The diagram shows a central cable with a joint. Labels with arrows point to various components: 'RETAIN CABLE JOINT' at the top, 'PULL-IN CABLE JOINT' on the right, 'PULL-IN CABLE JOINT' on the left, 'PULL-IN CABLE JOINT' at the bottom, 'PULL-IN CABLE JOINT' at the bottom left, 'PULL-IN CABLE JOINT' at the bottom right, 'PULL-IN CABLE JOINT' at the bottom center, 'PULL-IN CABLE JOINT' at the bottom left, 'PULL-IN CABLE JOINT' at the bottom right, and 'PULL-IN CABLE JOINT' at the bottom center.

Niche Testing - Air Permeability Tests to Characterize Niche Test Sites

- Boreholes are tested before and after niche excavation
- Four simple niches were excavated from the ESF Main Drift
- Niche 5 is located near the center of potential repository block, excavated from the Cross Drift

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Comparison of Lower Lithophysal and Middle Nonlithophysal Flow Paths

Lower lithophysal tuff may have:

- **Stronger capillarity**
(from liquid flow paths observed)
- **Higher permeability**
(from Niche 5 air injection tests reported on 5/1/00 and from Cross Drift systematic hydrologic characterization results)



Than middle nonlithophysal tuff

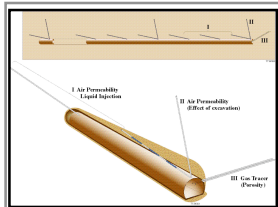
⇒ **Potentially Higher Seepage Threshold**

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Systematic Hydrological Testing in the Topopah Spring Lower Lithophysal Unit

- Supports UZ Seepage Model - Heterogeneity of fracture characteristics, permeability, and seepage
- Perform hydrological tests in 20-m long boreholes drilled at regular intervals (every 30 meters) along the Cross Drift regardless of specific features (fractures, lithophysal cavities etc.)
- Equipment systems (for air-k and liquid release tests) fitted on flatcar units are moved from one borehole station to another

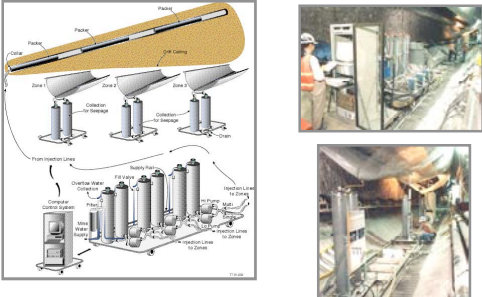


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Systematic Hydrologic Testing

Equipment System: Schematics and Actual Field Deployment



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Systematic Hydrologic Testing (Continued)

Systematic Approach Designed to Evaluate Spatial Heterogeneity

- Variability in formation response at different locations
 - Some of the test locations do not let any water enter the formation; all introduced water returned in overflow
 - Some locations show complete diversion of all water from entering the drift regardless of uptake rate
 - Most test zones show partial diversion of introduced water from entering the drift
- Flow characteristics common to all locations
 - Small fractures and lithophysal cavities connect to provide discrete, preferential flow paths
 - Participation of lithophysal porosity in liquid flow paths is small
- This variability is being addressed within the drift-scale seepage model

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PRELIMINARY

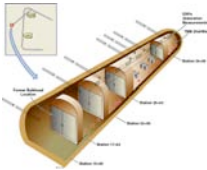
Cross Drift Bulkhead Investigations

- Evaluate flow and seepage processes in potential repository horizon rocks and Solitario Canyon Fault Zone in support of UZ Flow and Seepage Models
- Terminal 918m of the Cross Drift isolated from ventilation to observe in situ drift conditions and re-wetting after closing bulkheads
- Monitor for free liquid water from either seepage or condensation
- Multiple lines of evidence (e.g., water chemistry, moisture distribution) suggest condensation is dominant
- Ongoing and planned testing and analysis program in place to address observations

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Bulkhead Investigations (Continued)
Observations

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Geochemistry

- Consolidated sampling
- Laboratory studies
 - Environmental tracers
 - Fracture minerals
 - Hydrochemistry
 - Introduced materials (e.g., dust studies)

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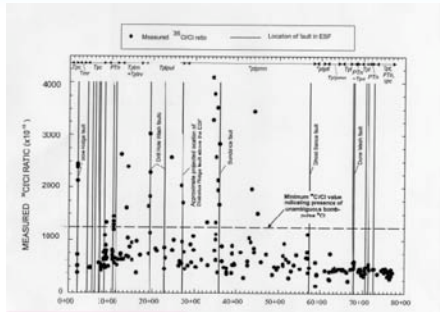
Objectives of $^{36}\text{Cl}/\text{Cl}$ Studies

- To develop and test alternative conceptual models for Unsaturated Zone (UZ) flow and transport, based on measurement and simulation of suitable environmental tracers
 - Specifically:
 - To evaluate flow and transport through the PTn and the role of faults and fractures in unsaturated zone flow and transport
 - To evaluate the significance of considering different temporal and spatial scales
- Program focused on systematic and feature-based samples from the Exploratory Studies Facility (ESF) and Cross Drift

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$^{36}\text{Cl}/\text{Cl}$ Results from ESF



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^{36}Cl Validation Measurements

- The goal of the ^{36}Cl measurements was to verify the presence of bomb-pulse ^{36}Cl in samples taken from ESF
- Accordingly, the sample preparation method was designed to detect the presence of bomb-pulse ^{36}Cl but not necessarily delineate the relative contributions of the other possible ^{36}Cl components

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Thermal History of the Unsaturated Zone Fluid Inclusion Studies

- The U.S. Geological Survey (USGS) studied the timing and distribution of secondary-mineral-hosted fluid inclusions
 - Fluid inclusions in calcite indicate that depositional temperatures have ranged from present-day ambient to as high as 90°C
 - Depositional temperatures are highest in the older parts of deposits
 - Calcite delta ^{18}O values correlate with and corroborate the fluid inclusion temperatures
 - Both the fluid inclusion and delta ^{18}O data indicate that calcite/opal deposition has been at or near present-day ambient temperatures for the past 2 to 4 m.y.

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Secondary Fracture Minerals

- Ongoing studies of fracture minerals
- Confirm slow mineral growth rates throughout the Quaternary
- Establish a linkage between climate variations and UZ percolation flux
- Add confidence to the UZ flow and transport models by integration of climate records

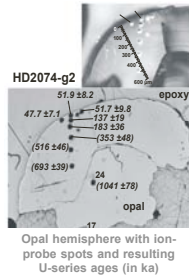
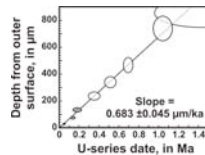
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Secondary Fracture Minerals (Continued)

U-series Ion-Probe Dating of Unsaturated Zone Opal

- Ion-microprobe data using ~35 μm -diameter spots traversing several individual opal hemispheres
- U-series ages indicate uniform average growth rates of 0.5 and 0.7 $\mu\text{m}/\text{k.y.}$ over the past ~1.5 million years - consistent with long-term average percolation fluxes



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Geochemistry of Pore Water

- Relevance of pore water compositions to the UZ hydrologic system
 - Tuffs contain several liters of water per m^3 of rock
 - Pore water may seep into drifts and contact waste packages
 - Evaporation of pore water on drift walls supplies salts to dust load
 - Pore water composition must be known to understand total hydrologic system

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Geochemistry of Pore Water

(Continued)

- Pore water is extracted from dry drilled core by
 - Compression of nonwelded tuffs and
 - Ultracentrifugation of welded tuffs in 150 gram batches
- Chemical (major and trace anions and cations) and isotopic (O, H, C, Sr, and U) analyses are conducted on extracted samples

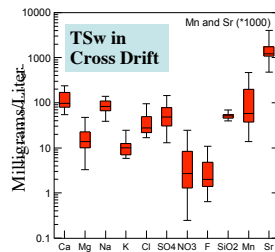
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Geochemistry of Pore Water

(Continued)

- Compositional Variability (n=28)
 - Variability at meter scale
 - Nitrate shows greatest variability
 - Silica shows least variability
 - Variability of alkaline earths is ± 60 percent
 - Variability of alkalis is ± 35 percent
 - Integrated with waste package environment and corrosion studies



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Coupled Processes

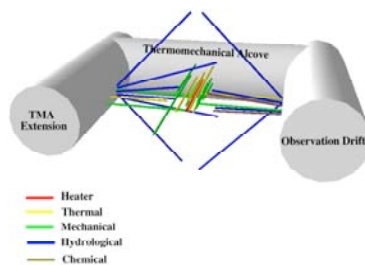
- Integrated laboratory and field testing program at a variety of spatial and temporal scales
- Robust approach to testing and modeling
 - Scoping analyses in support of test design
 - Pre-test predictive modeling
 - Predictions compared to measurements lead to model refinement and validation

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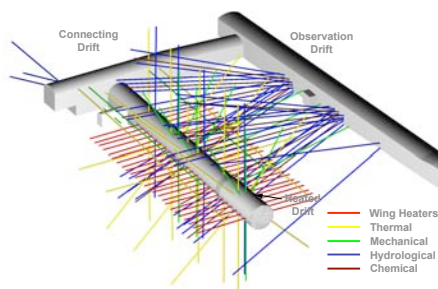




Single Heater Test – Borehole Perspective



Drift Scale Test



Probing THMC Processes - Drift Scale Test

Pre-Test Characterization

Laboratory	Field
T-Properties	Rock Classification
H-Properties	Fracture Mapping
M-Properties	Borehole Videos
MIN/PET	Air Permeability
Pore water	

Periodic Active Testing during Heating and Cooling

GPR	Liquid Saturation
Neutron log	
ERT	

Air Permeability : Fracture saturation and fracture aperture changes
Gas Sampling
Water sampling

Passive Monitoring during Heating and Cooling

- Temperature
- Displacement
- Strain
- Humidity
- Pressure
- Acoustic Emission (microfracturing)

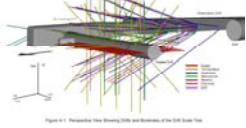
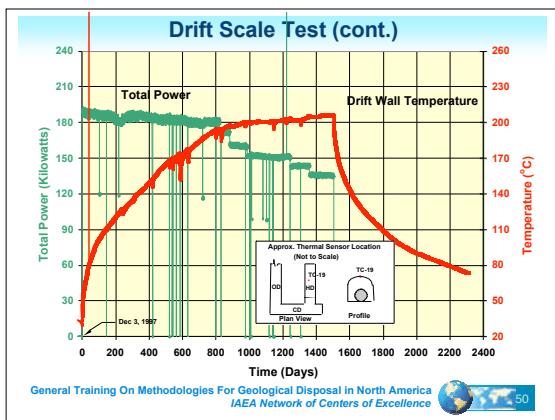
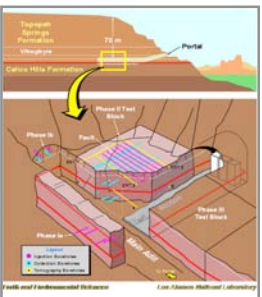


Figure 4.1: Representative View Showing Data and Monitoring of the Drift Scale Test

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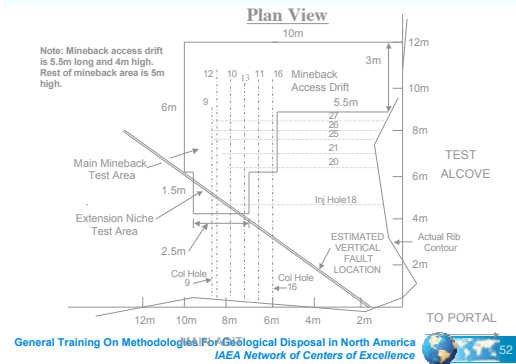
Busted Butte Unsaturated Zone Transport Test



- Evaluate influence of heterogeneities on flow and transport
- Evaluate other aspects of site, including fracture/matrix interactions and permeability contrast boundaries
- Consider colloid migration in unsaturated zone
- Test use of laboratory sorption data at field scale
- Calibrate and validate site-scale UZ flow and transport model
- Address scaling issues

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Busted Butte Phase 2 Post-Test Mineback Program



Busted Butte Unsaturated Zone Transport Test (Continued) Conclusions

- Busted Butte shows that rocks in the field behave in a manner similar to rocks in the laboratory with respect to capillary forces
- Permeability contrasts and unit boundaries appear to be more important for transport than fractures, at the flow rates used
- Busted Butte is consistent with the current conceptual model
- Busted Butte provides support for modeling parameters used in the site-scale flow model

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Summary

- Data collection and testing in ESF, Cross Drift, and Busted Butte were key components of site characterization program
- Ongoing underground activities continue to address uncertainties and provide additional confidence in natural and engineered systems analyses and models and design in support of License Application

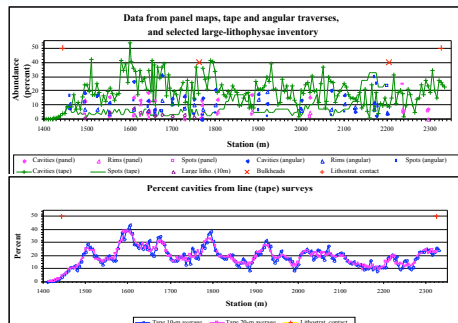
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Backup



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Lithophysal / Fracture Studies



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PRELIMINARY

Thermal-Mechanical Rock Properties (Continued) Pressurized Slot Test Results

Test	T-M unit	Location	Temperature	E (GPa)	ν
PST #1	Ttptpl	ESF 57+77	ambient	0.5	0.2
PST#2	Ttptul	ESF 63+83	ambient	3.0	0.2
PST#2	Ttptul	ESF 63+83	T>80°C	1.5	0.2
PST#3	Ttptpl	ECRB 21+25	ambient	0.7	0.3

- The estimated Young's modulus of Ttptpl and Ttptul is only a fraction of the value of Ttptmn modulus measured in the Thermal Test Facility (0.5~3.0 GPa vs. 20 GPa)
- It appears that the effects of lithophysae on mechanical properties of Ttptpl are more significant than anticipated
- Results are incorporated into drift degradation models



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PRELIMINARY

Thermal-Mechanical Rock Properties (cont.)



Uniaxial Compression Test on a Sample at 200 deg C (8/02)



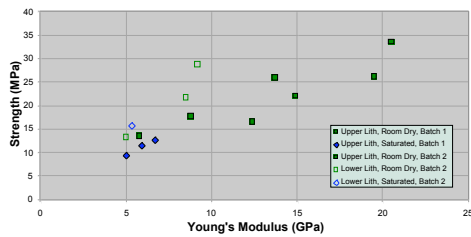
Thermal Expansion Test Sample (8/02)

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Thermal-Mechanical Rock Properties (Cont)

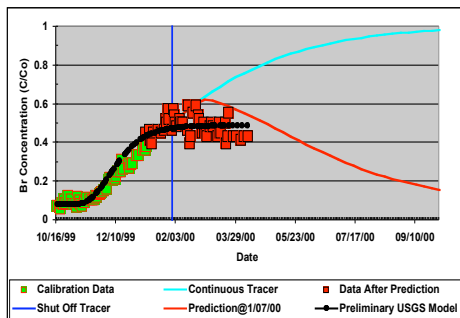
Laboratory Experiments on Large Samples of Topopah Spring Lithophysal Tuff at Room Temperature



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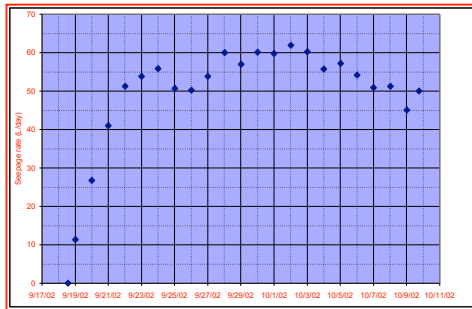
Alcove 1 Tracer Experiment



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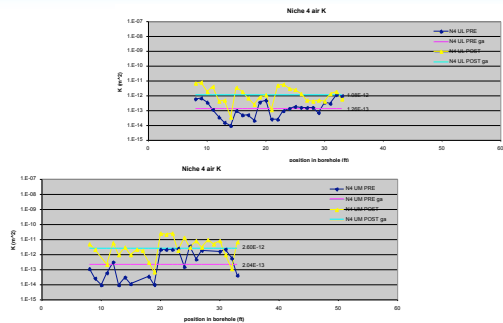
Alcove 8/Niche 3 Seepage Rates



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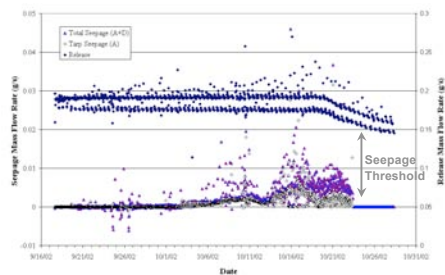
Permeability Enhancement from Niche 4 Excavation



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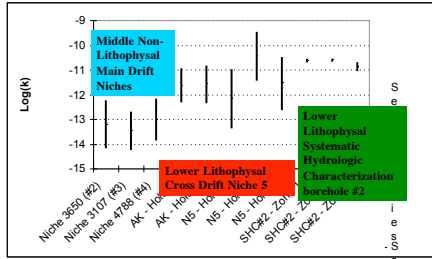
Niche 5 (Continued) Release and Seepage Mass Flow Rates Test #2 9-17-02



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Air Permeability Distributions Update with New Measurements by Systematic Hydrologic Characterization



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^{36}Cl Validation Study Status and Path Forward

- “Bomb-pulse” observed by LANL (samples from Exploratory Studies Facility walls, drill core from Niche #1, and Cross Drift)
- No “bomb-pulse” in LLNL and LANL validation samples
- Lowest $^{36}\text{Cl}/\text{Cl}$ values are in LLNL data for active leaches of validation samples
- No “bomb pulse” found by USGS/LLNL in recent analysis of Niche #1 drill core
- “Bomb-pulse” found by LANL in recent analysis of Niche #1 drill core

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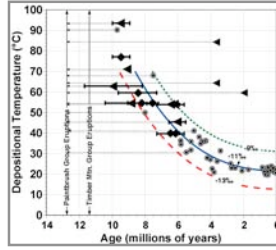
^{36}Cl Validation Study Status and Path Forward (cont.)

- Conceptual model for UZ flow and UZ process and Total System Performance Assessment (TSPA) models do not rely directly on the ^{36}Cl data and will not be modified based on validation results to date (i.e. remains consistent with original LANL results - conservative with respect to “fast paths”)
- Final USGS/LANL/LLNL report currently in progress - due date - Fall, 2004
 - Will include a path forward (further experiments for consideration)
- DOE is conducting a study by an independent third party to resolve the ^{36}Cl validation issue
 - New study will involve
 - Background investigation
 - Experimental design
 - Analytical effort
 - Final conclusion

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Temperature vs. Time in the Unsaturated Zone

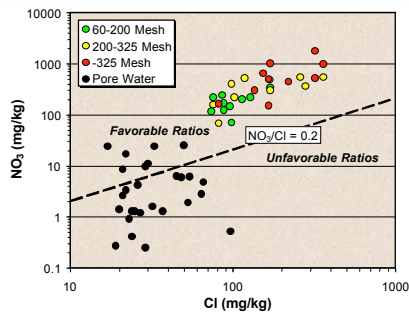
- Age of calcite deposition can be constrained by associated opal or chalcedony U-Pb or U-series ages
- Dated silica overlying calcite provides a minimum age; true calcite age falls along the dashed lines and may be substantially older
- Temperatures can also be calculated from calcite delta ^{18}O values, assuming a delta ^{18}O for the depositing water of -11‰ (shown as circled dots)
- Curves shown are best-fit regressions to the calcite delta ^{18}O temperatures for waters having a delta ^{18}O value of -13‰ , -11‰ , and -9‰ , similar to present-day meteoric water, and demonstrating
- The gradual cooling is consistent with heat provided by the formation and cooling of the batholith-scale upper crustal magma body that produced the 15 to 10 m.y.-old volcanic tuffs and alteration of the tuffs below the water table 11 to 9 Ma



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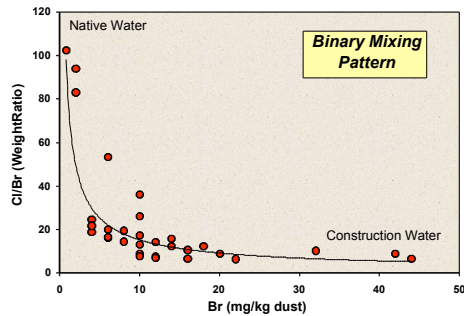
Dust Studies - Nitrate-to-Chloride Ratios in Soluble Dust Fractions



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Dust Studies (cont.) Mixing of Salts from Native Pore Water and Construction Water

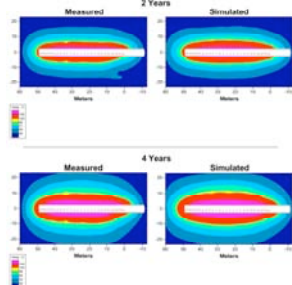


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Drift Scale Test: Thermal Isotherms: Vertical Slices Through Midlength of the Heated Drift

Thermal Isotherms:
Vertical Slices Through Longitudinal Axis of the Heated Drift



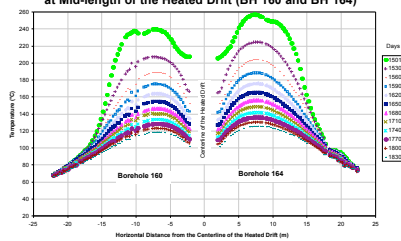
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Drift Scale Test (cont.)

Temperatures Parallel to the Wing Heaters Approximately
at Mid-length of the Heated Drift (BH 160 and BH 164)



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